Systems Engineering a Naval Railgun

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Abstract—An effective systems engineering process will provide the framework to enable the complex technical endeavor of railgun system design and development to transition from a set of research projects to a viable acquisition program. The detailed formulation and application of the railgun systems engineering process will be defined by government acquisition agents and the selected private sector contractors in accordance with United States (US) Department of Defense policy and regulation and in keeping with best systems engineering practices. Three factors that are critical to the success of the US Navy's Railgun Program include integrated product teams, risk management, and early systems engineering planning and commitment.

I. Introduction

The Navy's Electromagnetic Railgun Program currently seeks to provide technology maturity demonstrations of key performance aspects of an electromagnetic launcher, the associated pulsed power subsystem, and the guided hypersonic projectile, with the ultimate goal of introducing a railgun system possessing military utility into the operating forces of the United States (US) Navy. As with any complex military system development, the program will face many challenges in meeting the cost, schedule, and performance goals for the future Railgun Acquisition Program. This paper describes the type of systems engineering process that will make the Navy railgun a reality, and it identifies several high-priority activities that will be required for its success.

Delivering energy on target at a significantly longer range than existing or near-term gun systems, at a given rate of fire, is the fundamental capability for a railgun weapon within the Strike and Naval Surface Fire Support mission areas. A tactical railgun system will require an unprecedented amount of electrical power for its operation, so the development of an integrated power system in Navy warships is necessary to make an operational railgun weapon system a reality.

The confluence of two earlier efforts makes the railgun a viable candidate as a shipboard strike and surface fire support weapon system: first, the decision to change fundamentally the nature of US Navy warship propulsion from mechanical drive trains to integrated electric drive systems; and second, early work done by the US Army and

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the US Marine Corps on electromagnetic guns for armored vehicles. Fig. 1 illustrates the potential capability of a railgun weapon system. As the figure shows, a railgun weapon system will draw on significant reservoirs of ship power to bring force to bear at ranges of hundreds of miles from the ship, at a per-round cost far below that of present deep land attack weapons; this system would fundamentally change the fight. The fundamental paradigm shift to the electric warship will allow sharing of the installed prime mover power almost instantaneously among propulsion, hotel electrical loads, and weapons, and promises to cause fundamental changes in future naval force capabilities. Reference [1] gives a future-Navy perspective on the impact of integrated power systems, naval rail guns, and other directed energy weapons.

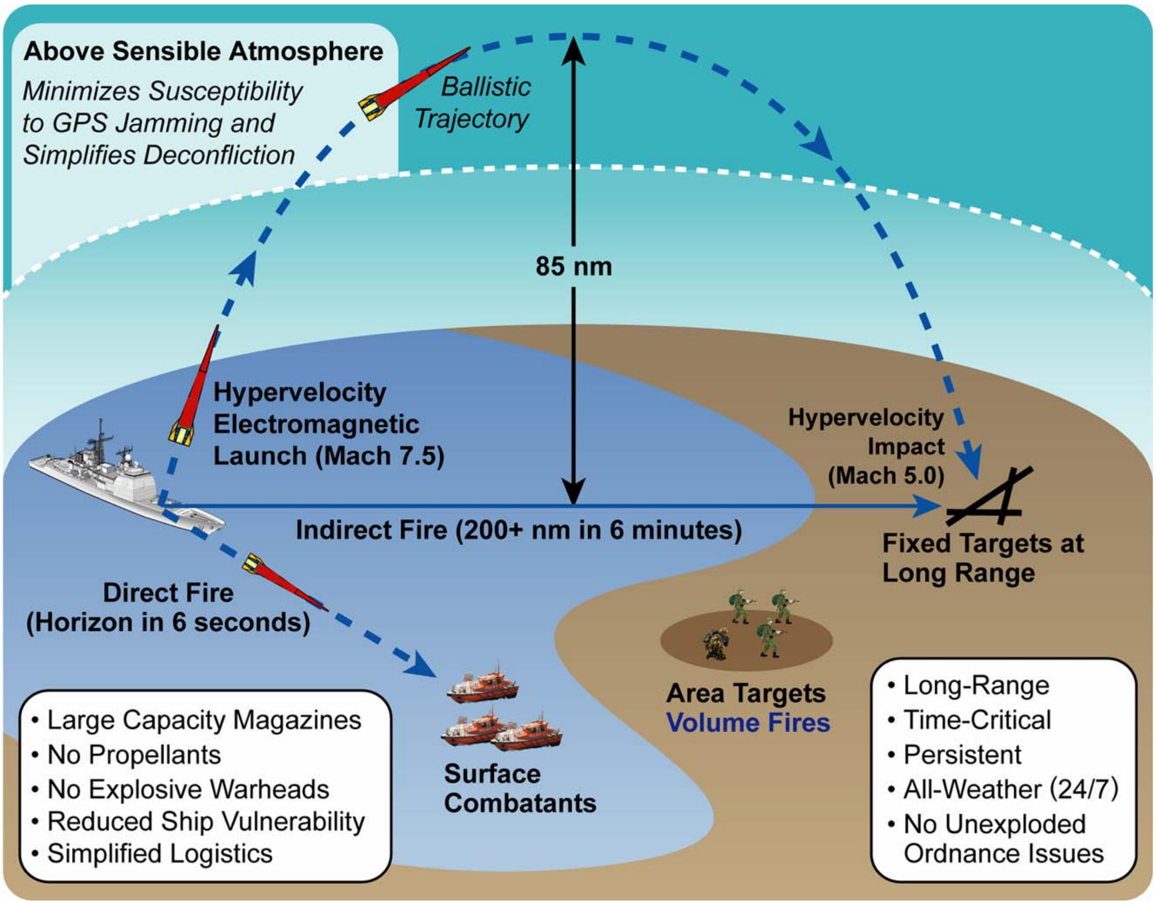


Fig. 1. Railgun weapons system capability
(Source: Office of Naval Research)

While the ability to propel guided munitions hundreds of miles offers significant tactical and strategic capabilities, the technical challenges should not be underestimated. Fig. 2 illustrates a top-level railgun weapon system architecture. The profound challenges include the following: a projectile guidance and control system tolerant of the high G-forces of launch, the enormous amounts of pulsed energy needed for firing, unprecedented thermal management requirements, gun rail material properties, heretofore never achieved power management control, cooling and support systems, potentially serious electromagnetic interference effects, and many others.

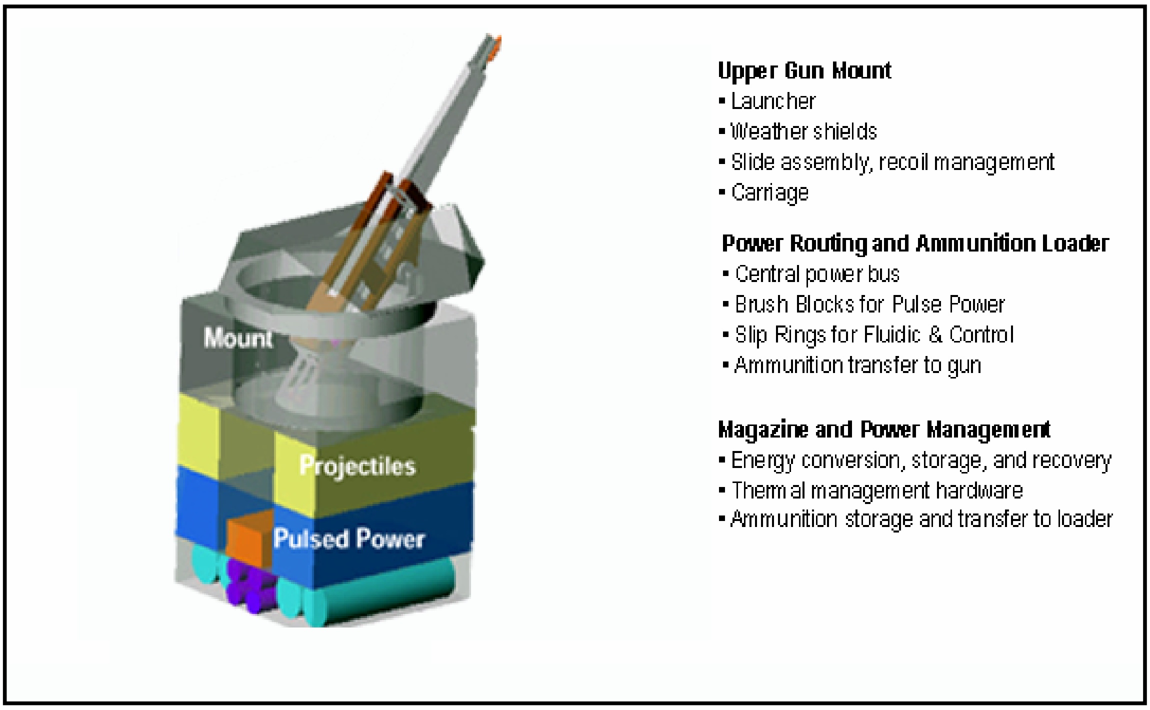


Fig. 2. Notional railgun weapon system architecture
(Source: Office of Naval Research)

II. SYSTEMS ENGINEERING PROJECT LIFE CYCLE

To design, develop, and deploy an effective, maintainable railgun weapon system, the Navy will need to establish a disciplined systems engineering program in keeping with US Department of Defense (DoD) regulations [2]. This systems engineering program will initially focus on defining operational needs, identifying the functionality required to meet those needs, and establishing a balanced set of requirements, and then will proceed with design synthesis and system validation, while considering the complete problem from inception to disposal. Fig. 3 illustrates the principal steps of this process, which begins with the transformation of an operational need into a set of top-level requirements that guide the evolving design. The definition and allocation of customer-validated railgun system functions and requirements is a necessary first step to define a top-level system architecture and to establish a functional baseline that will provide the basis for component trade-off studies. These studies, in turn, will help refine the railgun system functional baseline and will enable the definition of subsystem requirements and a system test and evaluation plan.

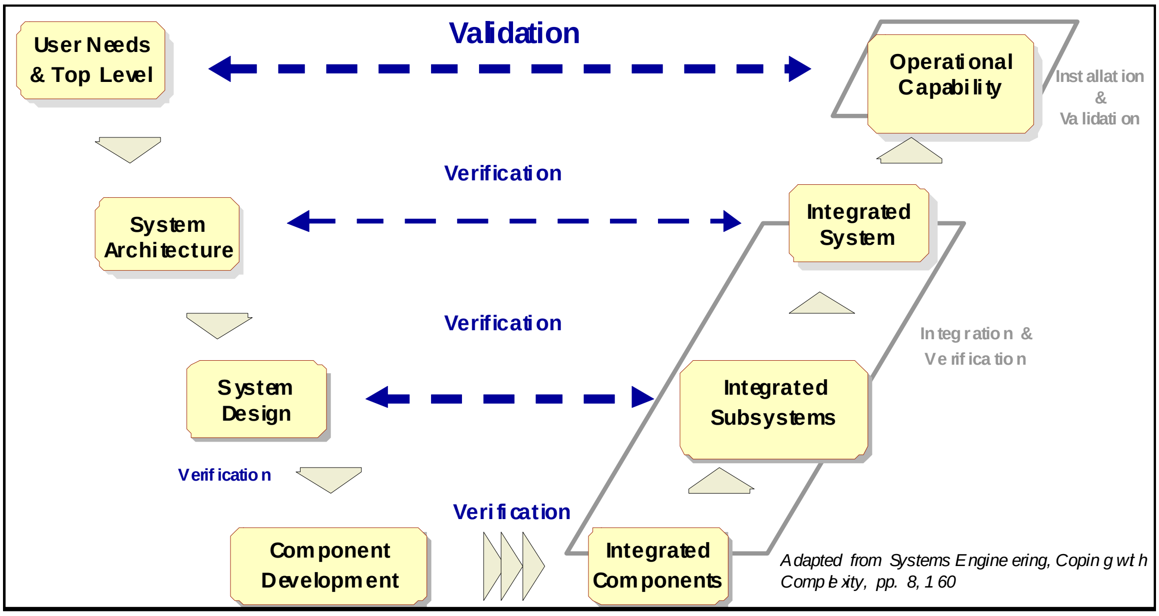


Fig. 3. Systems engineering process

Fig. 4 depicts the DoD life cycle framework within which the railgun weapon systems engineering activities will occur. This framework represents the top-level policies and procedures defined in [2], which forms the basis for the railgun acquisition and systems engineering planning described in this paper. Within this framework, the flow of the systems engineering process is iterative within any one phase of the acquisition process and is recursive at lower and lower levels of the system-subsystem-component hierarchy. Using controlled baselines, systems engineering processes will allow an orderly progression from one level of development to the next, more detailed level; this will apply to the system, subsystems, and lower-level components, as well as to the supporting and enabling systems used for the production, operation, training, support, and disposal of that system. Technical management processes and activities, such as trade studies or risk management activities, can be expected to identify specific, non-optimal, railgun weapon system requirements, interfaces, or design solutions and provide the basis for engineering change to increase system-wide performance, to achieve cost savings, and to meet scheduling deadlines. The many systems engineering subprocesses will not only allow a disciplined flow-down of railgun requirements into system design, but they will also provide the integrated framework within which emergent user needs and technology opportunities can continue to influence how requirements, as a collective whole, are defined, analyzed, decomposed, traded, managed, allocated, designed, integrated, tested, verified, and validated to ensure a balanced approach to meeting cost, schedule, performance, and suitability thresholds.

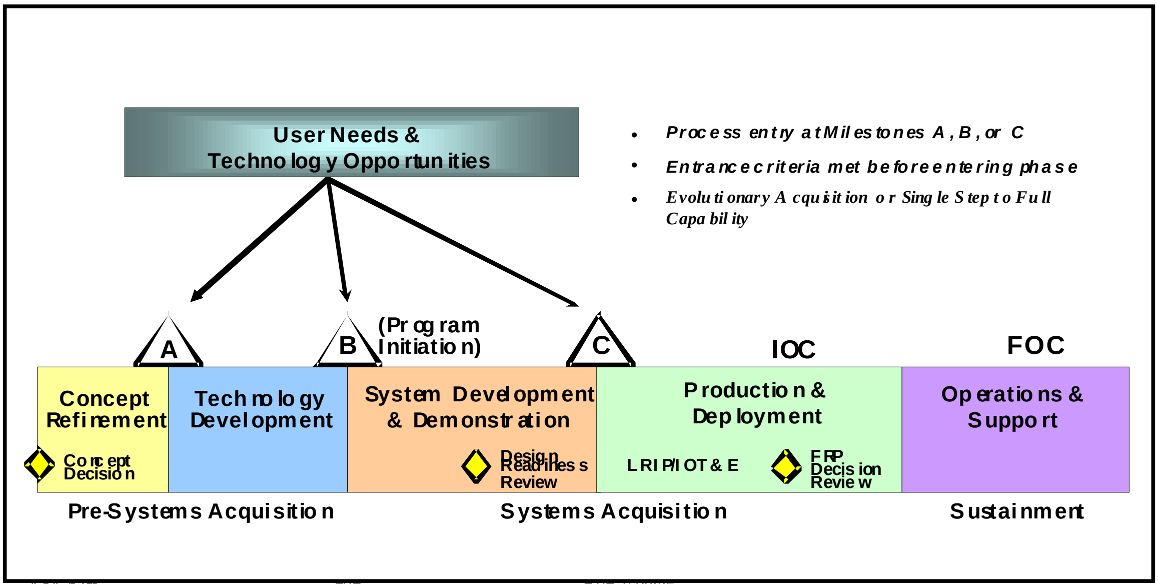


Fig. 4. Defense acquisition management framework
(from DoD Instruction 5000.2 of May 12, 2003)

Concept Refinement

The Concept Refinement phase will improve the initial model of the electromagnetic railgun system operational concept and will develop a technology development strategy (TDS). This phase will include experiments and other technology-maturation activities conducted at the component and subsystem levels. Initial systems engineering activities will concentrate on the development of processes necessary to support the technology development activities. The requirements management activities will result in an approved railgun weapon system initial capabilities document (ICD) (one of the documents that results from a DoD requirements generation process [3]) based on the analysis of potential concepts across the DoD components, international systems from allies, and cooperative opportunities. Additionally, the concept refinement activities will produce an approved plan for conducting an analysis of alternatives (AoA) for the selected concept, which will be documented in the approved ICD.

The ICD and the AoA plan will guide the Concept Refinement phase. The AoA will refine the selected concept documented in the approved ICD. The AoA will assess the critical railgun technologies associated with these concepts, including technology maturity, technical risk, and, if necessary, technology maturation and demonstration needs. The ongoing railgun system science and technology activity will support this effort by validating technology readiness and by providing input to the risk assessment. The AoA results will provide the basis for the TDS document, which the milestone decision authority (MDA) will review for approval at Milestone A.

Technology Development

The Technology Development phase of railgun weapon system development will reduce technology risk and determine the appropriate set of technologies to integrate into a full system. The Technology Development phase will provide a continuous technology discovery and development process that will reflect close collaboration among the science and technology community, the user, and the system developer. It is an iterative process designed to assess the viability of technologies while simultaneously refining user requirements. The Railgun Program will enter the Technology Development phase at Milestone A, when the MDA has approved the TDS. The ICD and the TDS will guide this effort. Multiple technology development demonstrations with the electromagnetic launcher, hypersonic projectile, and pulse forming network/power supply will facilitate user and developer agreement that a proposed technology solution is affordable, militarily useful, and based on mature technology.

Railgun weapon systems engineering activities will include continued requirements management, risk management, configuration management, and interface management. Data management—the acquisition, distribution, protection, and storage of technical data—will play an important role during the Technology Development phase. This data management effort will address the following: the data associated with system development, the modeling and simulation used in developments or tests, test and evaluation, installation, parts, spares, repairs, usage data required for product sustainment, and source and/or supplier data.

During the Technology Development phase, systems engineering processes will identify, and in some cases develop, the necessary technologies for the preferred system solution. Railgun systems engineering will provide comprehensive, iterative processes to accomplish the following activities:

1. Convert each required capability into a system performance specification,
2. Translate user-defined performance parameters into configured systems,
3. Integrate technical inputs of the entire design team,
4. Manage interfaces,
5. Characterize and manage technical risk,
6. Transition technology from the technology base into program-specific efforts, and
7. Verify and validate that designs will meet operational needs.

The Railgun Program will exit the Technology Development phase when an affordable increment of militarily useful capability has been identified, the technology for that increment has been demonstrated in a relevant environment, and a railgun weapon system can be developed for production within a short timeframe (normally less than five years), or when the MDA decides to terminate the effort. During the Technology Development phase, the user will prepare a capability development document (CDD) to support program initiation and will clarify how the program will lead to joint warfighting capability. The CDD will build on the ICD and provide the detailed operational performance parameters necessary to design the proposed system. A Milestone B decision will follow the completion of the Technology Development phase.

System Development and Demonstration

The railgun weapon system will enter the System Development and Demonstration (SDD) phase at Milestone B. The SDD phase will ensure operational supportability with particular attention to minimizing the logistics footprint. The purposes of the SDD phase include the following:

1. Develop and qualify the railgun system;
2. Reduce integration and manufacturing risk;
3. Certify operational supportability with particular attention to reducing the logistic footprint;
4. Implement human systems integration;
5. Develop a producible design;
6. Ensure affordability and protection of critical program information; and
7. Demonstrate system integration, interoperability, safety, and utility.

Based upon the technologies selected and integrated during the Concept Refinement and Technology Development phases, the SDD phase will define the acquisition program structure, the system architecture, and the system elements down to the configuration item level. The SDD phase will allocate the system design requirements down to the major subsystem level and will refine them to reflect developmental and operational test results and iterative systems engineering analyses. Following a successful design readiness review, the SDD phase will culminate in Milestone C.

Production and Deployment

The Production and Deployment phase will commence at Milestone C and encompass low-rate initial production and full-rate production and deployment, separated by a full-rate production decision review. As the railgun components combine into a system and undergo ship integration, the test and evaluation process might reveal issues that require system improvements or redesign. The initial manufacturing processes might also reveal unanticipated issues that could require changes in product design, manufacturing, or other supporting processes. Low-rate initial production will result in completion of manufacturing development and demonstration of an operational capability that will satisfy mission needs. Full-rate production and deployment will deliver the required quantity of systems and supporting material and services.

Operations and Support

The objective of the Operations and Support phase is the execution of a railgun system support program that meets operational support performance requirements and sustains the system in the most cost-effective manner throughout its total life cycle. This phase also includes safe disposal when the system reaches the end of its useful life.

III. KEY FACTORS FOR A SUCCESSFUL RAILGUN SYSTEMS ENGINEERING PROGRAM

A successful, effective systems engineering program will require a number of factors to be present during the Navy's Railgun Acquisition Program. There are too many to discuss within the scope of this paper, but three factors have high priority and should be emphasized: *integrated product teams* (IPTs), *risk management*, and *systems engineering planning documented by a Systems Engineering Plan* (SEP).

Effective Systems Engineering Integrated Product Teams

The Railgun Weapon Systems Engineering (SE) Integrated Product Team (IPT) will provide technical management guidance across the government, prime contractors, subcontractors, and suppliers. The SE IPT will generate and will update the Railgun Weapon SEP and the other documentation identified within the plan. As shown in Fig. 5, one of the primary responsibilities of the SE IPT is coordination and management of the major interfaces among the other technical IPTs. The Railgun Weapon SE IPT and the director of systems engineering will identify and conduct periodic program reviews to ensure the completion of major milestone tasks. Finally, the SE IPT will provide the overarching technical program guidance and the forum for each of the technical teams to merge their specific data and products into the overall railgun/ship program.

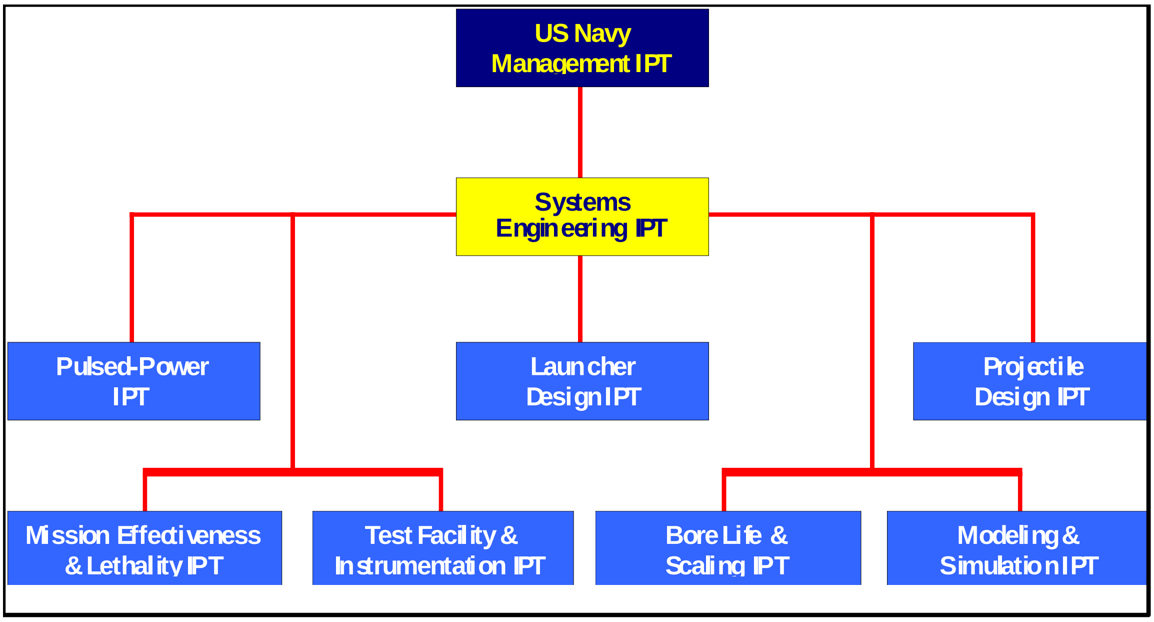


Fig. 5. Railgun weapon system integrated product team organization

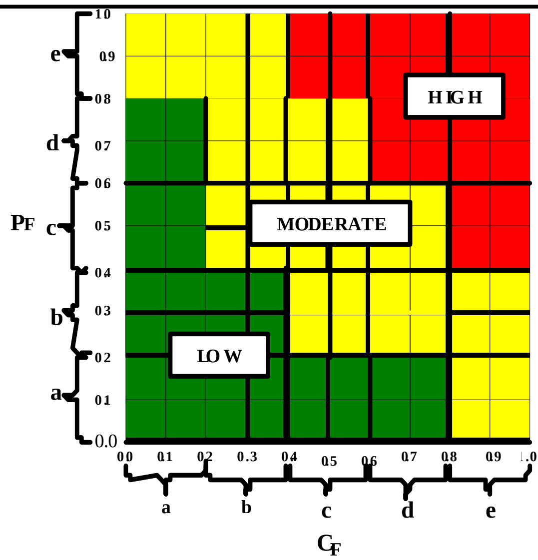
Railgun Risk Identification and Control

An early phase risk identification and control program is an essential part of the systems engineering of a railgun weapons system. Risk matrices are useful for comparing risks either within a given technical area or across all technical areas as a "roll-up" risk picture. Risk severity for each risk element becomes readily visible by plotting probability of failure (P_F) against consequence of failure (C_F). Estimates of P_F and C_F are somewhat subjective but typically rely on information from one or more of the following sources: comparisons with other systems, relevant lessons-learned studies, experience, results from tests and prototype development, data from engineering or other models, specialist and expert judgments, analysis of plans and related documents, modeling and simulation, and sensitivity analysis of alternatives [4].

The railgun systems engineering program will include an ongoing assessment of P_F and C_F. Fig. 6 illustrates a sample risk assessment matrix showing risk as P_F plotted against C_F. P_F and C_F do not always weigh equally; for example, severe consequences can make the overall risk unacceptable even though the P_F may be low. The combination of P_F and C_F determine an overall risk factor (RF), indicated either as the numerical product of P_F and C_F (with values between 0.0-1.0), or by a graphical depiction of C_F versus P_F. RF will be used to identify, track, and manage Railgun Program risks.

Probability Ratings (P_F)

Level: Quantitative	Level: Qualitative	Likelihood
0.0-0.2	a	Remote
0.2-0.4	b	Unlikely
0.4-0.6	c	Likely
0.6-0.8	d	Highly Likely
0.8-1.0	e	Near certainty



Consequence Ratings

Level: Quantitative	Level: Qualitative	Impact
0.0-0.2	a	Minimal impact
0.2-0.4	b	Some impact
0.4-0.6	c	Moderate impact
0.6-0.8	d	Major impact
0.8-1.0	e	Unacceptable

Fig. 6. Sample risk area assessment matrix

Systems Engineering Plan

As the Naval Railgun Program matures and evolves, an SEP, described in [5], will be used to guide program acquisition. The Defense Acquisition University describes the

SEP as a detailed formulation of actions that should guide all technical aspects of an acquisition program such as the Railgun Program. The program manager will establish the SEP early in the program formulation and update it as necessary. It is intended to be a living document, tailored to the program, and a roadmap that supports program management by defining comprehensive systems engineering activities and clarifying both government and contractor technical roles and responsibilities.

The SEP describes the overall technical approach of the program, including systems engineering processes; resources; and key technical tasks, activities, and events, along with their metrics and success criteria. Important elements of the plan will include the systems engineering processes to be applied during the program, the technical baseline approach of the railgun system, the use of technical reviews, and the organization and process for the program's IPTs. SEP development will follow the guidelines established by DoD, creating an intentionally dynamic document that is modified as necessary to reflect evolving program approaches, risk management, acquisition decisions, and other emerging influences on customer requirements and program strategies.

IV. SUMMARY

An effective systems engineering process will provide the framework to enable the complex technical endeavor for the railgun system design and development to transition from a set of research projects to a viable acquisition program. This paper has outlined this process. The detailed formulation and application of the railgun systems engineering process will be defined by government acquisition agents and the selected private sector contractors in accordance with DoD policy and regulations and in keeping with best systems engineering practices. Three factors that will be critical to the success of the Railgun Program are IPTs, risk management, and early systems engineering planning and commitment.

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